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The fiber design and an analytical model to predict its optical performance have both been validated. These fibers demonstrate improved bending-loss performance in the 1.55-μm wavelength band. Glass and coating diameters of 80 and 135 μm, respectively, were achieved. As predicted by the model, tight confinement of the propagating optical mode to the fiber's core greatly reduces the sensitivity to bending losses.

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INVESTIGATIONS INTO OPTICAL FIBERS FOR CANISTERIZED DATA LINKS

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ABSTRACT

Advanced single-mode optical fiber designs for canisterized data links for tethered weapons and expendable communication buoys were investigated. Where current telecommunication-grade fibers fall short in terms of packaging and bending loss, the new design shows promise in both these areas. Reduction of both the glass and coating diameters were achieved in addition to improved performance in bending losses.

The fiber design and an analytical model to predict its optical performance have both been validated. These fibers demonstrate improved bending-loss performance in the 1.55-μm wavelength band. Glass and coating diameters of 80 and 135 μm, respectively, were achieved. As predicted by the model, tight confinement of the propagating optical mode to the fiber's core greatly reduces the sensitivity to bending losses.

INTRODUCTION

Fiber-guided weapons and communication buoys require optical fibers that can be precision wound onto a bobbin and payed out from these platforms as an expendable data link. Fiber-guided weapons currently in development include the Navy's SEA RAY, the Army's FOG-M, and the Air Force's FOG-D systems. The Navy is also developing expendable buoys for submarine-to-surface communication with a fiber data link. Fibers offer advantages of secure two-way transmission with enormous bandwidth and minimum impact on system size and weight. However, smaller diameter and more bend-loss resistant fibers are needed for the operating ranges these systems require. Conventional single-mode telecommunication (telco) fibers with 250-μm outside diameters (ODs) fall short of fulfilling these requirements in both size and bend-induced losses.

To investigate the feasibility of reduced-diameter, bend-loss resistant fibers, a 90-μm glass diameter fiber with a coating OD of 180 μm was designed, fabricated, and tested. Later, an 80/135-μm fiber was fabricated and tested. The test results showed at least an order of magnitude improvement in bend-induced losses at λ=1.55 μm over telco fibers. This improvement was accomplished by confining the fundamental propagating mode to the core more tightly than in a telco fiber. In a parallel effort, a microbending model for fibers on a payout bobbin was developed to increase the understanding of fiber bend-loss performance. By measuring optical properties in a short fiber sample, bend-loss characteristics could be assessed.

This paper summarizes the results of our investigation into fibers for expendable data links. The approach in developing the 90/180-μm and 80/135-μm fibers is discussed first. This is followed by discussions of the model and macrobending- and microbending-loss performance of the fibers developed.

APPROACH

Reducing the fiber OD results in a volume and weight savings in the data link. However, bending-loss sensitivity increases as diameter and coating thickness are reduced. Therefore, the optical design of the fiber must be improved to reduce the bending losses. Fibers D and E described in Table 1 are reduced-diameter fibers designed for tight confinement of the LP_{01} mode at λ=1.55 μm for improved bending-loss performance. The mode-field radii (MFR) of the fibers are the root-mean-square width of the electric-field distribution in the fibers and indicate the degree to which the LP_{01} mode is confined to the core. Bending losses depend strongly on this parameter. Improved mode confinement was accomplished by increasing the GeO_2 concentration in the core to raise its refractive index relative to the cladding and to produce a high numerical aperture (NA). λ=1.55 μm was chosen as the wavelength of operation to take advantage of low Rayleigh-scattering losses and potential for very long distance transmission. Figure 1 illustrates the relative size difference between Fiber D and a conventional telco fiber.

To validate the design of Fibers D and E, test results were compared with results of a typical telco and dispersion-shifted (DS) fiber designs. Fiber A is a telco fiber and is included in Table 1 to illustrate its poor bending performance. Fiber B is a commercially-available DS fiber which exhibited improved bending performance, but was still found to be only marginally acceptable for payout applications. Fiber C is also a DS fiber but has a reduced OD and clearly demonstrated that reducing fiber OD increases bending losses. Severe bending losses prevented an accurate measurement of fiber attenuation, and no further testing on the fiber was performed. The results of these tests are summarized in Table 1 and are discussed in more detail in the following section.

This work was performed in-house under NOSC Project No. ZE65.

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RESULTS

WINDING-INDUCED MICROBENDING LOSSES

There are two types of bending losses on a payout bobbin: microbending and macrobending. Microbends are small perturbations of the fiber axis which cause the fundamental LP_{01} mode to couple into a higher order LP_{11} mode. The higher order mode is not guided and eventually radiates out of the fiber. These microbends occur at fiber crossovers in a payout bobbin formed because each layer of fiber is wound into a helix. Each pair of contiguous layers forms helices of opposite directions. Consequently, a fiber crosses over the layer beneath it twice per wrap. As the coating thickness is reduced, these crossovers become more severe. These crossovers were modeled as Gaussian-shaped perturbations of the fiber axis as illustrated in Fig. 2, where Y_0 is the amplitude, A is the half-width, and L is the distance between crossovers.[1] Since crossovers occur twice per wrap, L is half the bobbin circumference. When Fibers A and B were precision wound on 11.4-cm-OD bobbins, Y_0 and A were 35 μm and 1 mm, respectively. Figure 3 shows 10 km of Fiber B wound on the bobbin. When Fiber D was precision wound, Y_0 and A were 25 μm and .75 mm, respectively.

To assess the losses that occur in these crossovers, the power spectrum of the Gaussian-shaped crossovers was computed. The loss, α, in equation (1) is proportional to the power spectrum, $\phi(\Omega)$, evaluated at the spatial frequency difference, Ω, between the LP_{01} and LP_{11} modes.[2]

$$\alpha \propto \phi(\Omega) , \tag{1}$$

where $\Omega = 2/(kn\omega^2)$

$k = 2\pi/\lambda$

ω = mode-field radius

and n = core refractive index.

Figure 4 illustrates the power spectra and spatial frequency differences for Fibers A, B, and D. It shows that Fiber D should exhibit the least microbending losses, while Fiber A should exhibit the greatest losses.

The spatial frequency difference between the LP_{01} and LP_{11} modes were determined by measuring the mode-field radii in the fibers. First, the far fields were measured by launching a 1.55-μm laser into 2-meter lengths of the fibers and rotating a PIN detector in an arc in the plane of the fiber output. Then the far fields were converted to near fields through an inverse Hankel transform.[3] The near fields are illustrated in Fig. 5. The fields in Fiber D are confined most tightly to the core, while the fields in Fiber A are most loosely confined. These are reflected in the mode-field radii for the fibers in Table I.

Figures 6, 7, and 8 show the spectral attenuations of Fibers A, B, and D, respectively. The spectral attenuations were measured before precision winding and repeated after winding. The differences between the losses were attributed to microbending at the crossovers. The microbending loss in Fiber A was about 0.2 dB/km at λ = 1.55 μm, while the loss in Fiber B was only about 0.02 dB/km. Spectral attenuation measurements before winding for Fiber D were not available, but the data in Fig. 8 indicate no evidence of microbending at λ = 1.55 μm. This was confirmed by measuring the loss distribution with an optical time-domain reflectometer (OTDR) at λ = 1.55 μm, as shown in Fig. 9.

To investigate microbending further, the attenuations in Fibers B and D at λ = 1.55 μm were measured as the bobbins were temperature-cycled. At -60° F the loss increase in Fiber B averaged 0.2 dB/km, while in Fiber D the loss increase was only 0.05 dB/km.

MACROBENDING LOSSES

The second cause of losses in a precision-wound bobbin is macrobending, where the fiber is bent into a constant radius of curvature. This occurs at the peel point during fiber payout because the direction of fiber payout is nearly perpendicular to the fiber winding. The severity of the bends depend on the fiber size, its stiffness, payout speed, and shear strength of the adhesive used to hold the fiber in place on the bobbin. Although the exact curvature of the bends are not known, bend tests were performed on all of the fibers to determine relative bending performance.

Figure 10 shows the losses between 1.1 and 1.7 μm for a half turn around a 4.8-mm-diameter mandrel. (The losses for Fiber A were not displayed since they were greater than 5 dB at all of the wavelengths.) In these bends, the magnitude of the fields far from the core determine the amount of loss for a given bend.[4] The fields far from the core, or "tails," must propagate faster than the fields nearest to the core's center, but can never exceed the speed of light in the material. Consequently, optical power couples into radiation modes if these "tails" are required to exceed the speed of light in a bend. To minimize losses in a bend, the "tails" must be minimized.

The reason for improved macrobend-loss performance in Fibers D and E over Fiber B is obvious. The fields in Fiber B far from the core are much larger that those in Fibers D and E, as shown in Fig. 5. The performance of Fibers D and E is similar to within measurement error, since their fields far from the core are also similar. A note of interest is that although the macrobending performance in Fibers D and E is similar, the microbending performance in Fiber D should be better due to its smaller mode-field radius.

SUMMARY

In this exploratory development investigation reduced-diameter, bend-loss resistant optical fibers were developed for use in expendable data links. Fibers of 90 190-μm and 80 135-μm OD with excellent microbending and macrobending performance at λ = 1.55 μm were designed, fabricated, and tested. A microbending model for payout spools was also developed to advance the understanding of excess losses in payout bobbins. This technology has been transitioned as a major task in the Navy's SEA RAY program sponsored by NAVAIR.

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3 Anderson, W.T. and Philen, D.L., "Spot Size Measurements for Single-Mode Fibers—A Comparison of Four Techniques," *Journal of Lightwave Technology*, Vol. LT-1, Mar 1983, pp. 20-26.

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Table I. Fibers Tested.

	Fiber A	Fiber B	Fiber C	Fiber D	Fiber E
Type	telco	DS	DS	High NA	High NA
Glass dia. (μm)	125	125	80	90	80
Coating OD (μm)	250	250	185	180	135
Attenuation (dB km) @ λ=1.55 μm	0.23	0.20	*	0.32	0.28
λ_c (μm)	1.21	1.14		1.42	1.32
MFR** (μm) @ λ=1.55 μm	5.55	4.3		3.65	3.35
Macrobend loss[1] (dB)	30.4	20.7		0.06	0.13
Precision-winding loss[2] (dB km)	0.16	0.02		< 0.01	
Temperature test[3] (dB km)		0.2		0.05	

* Too much microbending to measure accurately on shipping spool.

** Mode-field radius

[1] Excess loss @ λ = 1.55 μm in ½ turn on a 4.8-mm dia. mandrel

[2] Microbending loss @ λ = 1.55 μm

[3] Excess loss in @ λ = 1.55 μm at -60° F

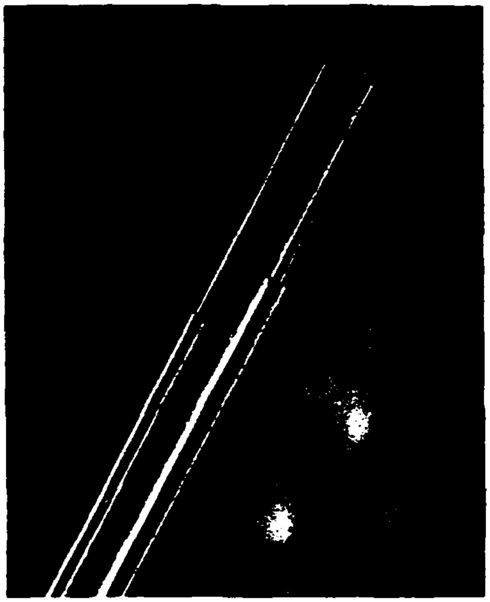

Fig. 1. The Relative Size of Fiber D (left) and a Conventional Telco Fiber.

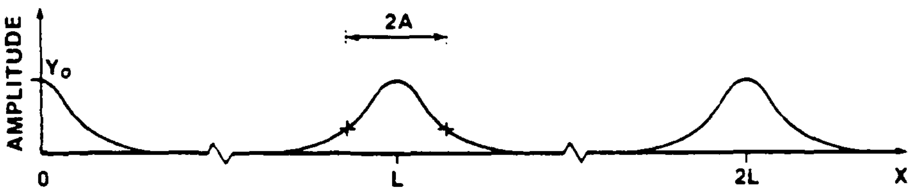

Fig. 2. Gaussian-Shaped Crossovers.

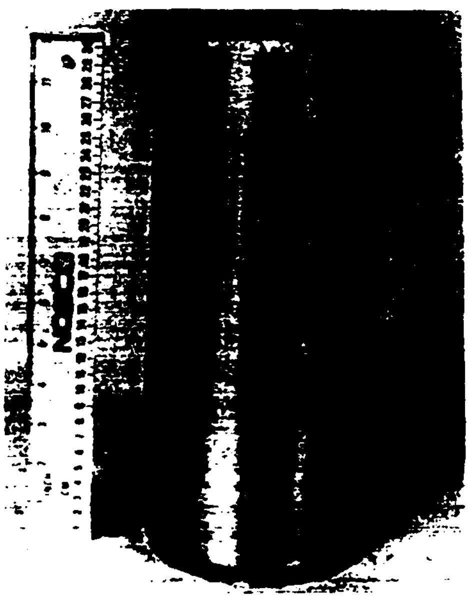

Fig. 3. Ten Kilometers of Fiber B Wound on the Bobbin.

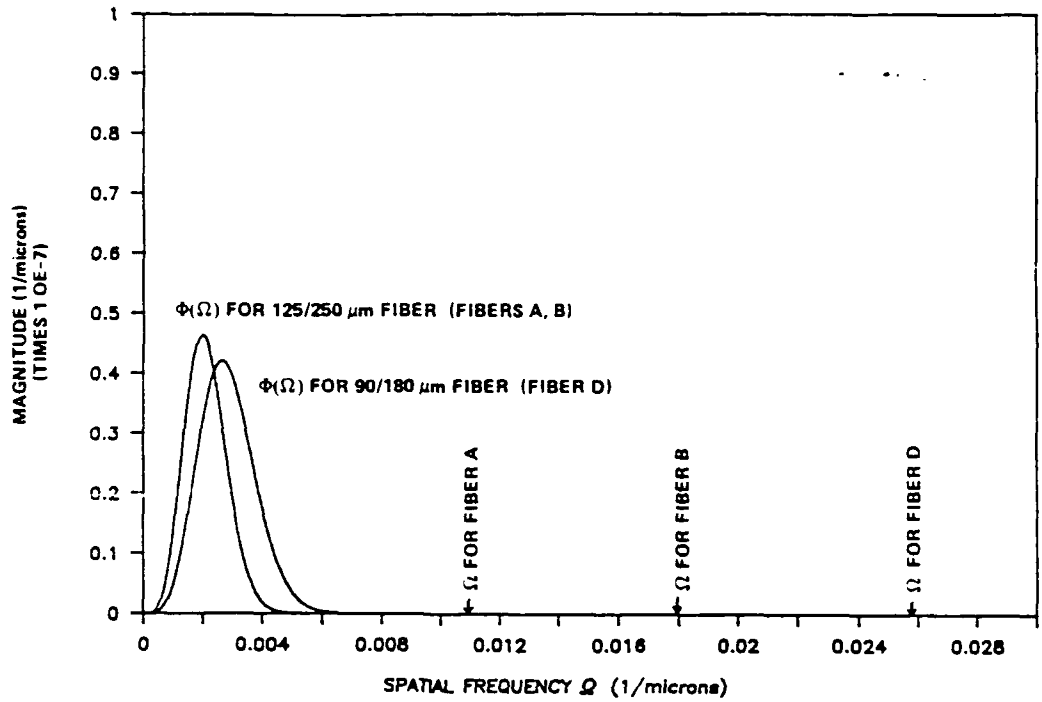

Fig. 4. Crossover Power Spectrum.

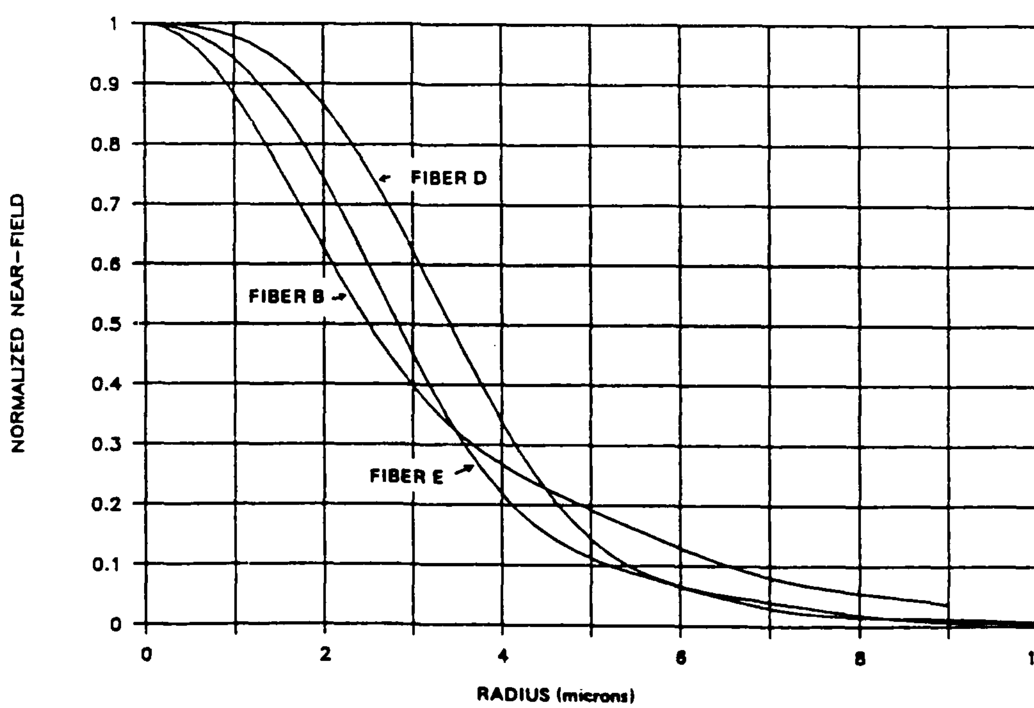

Fig. 5. Near Field-Patterns at 1.55 Microns.

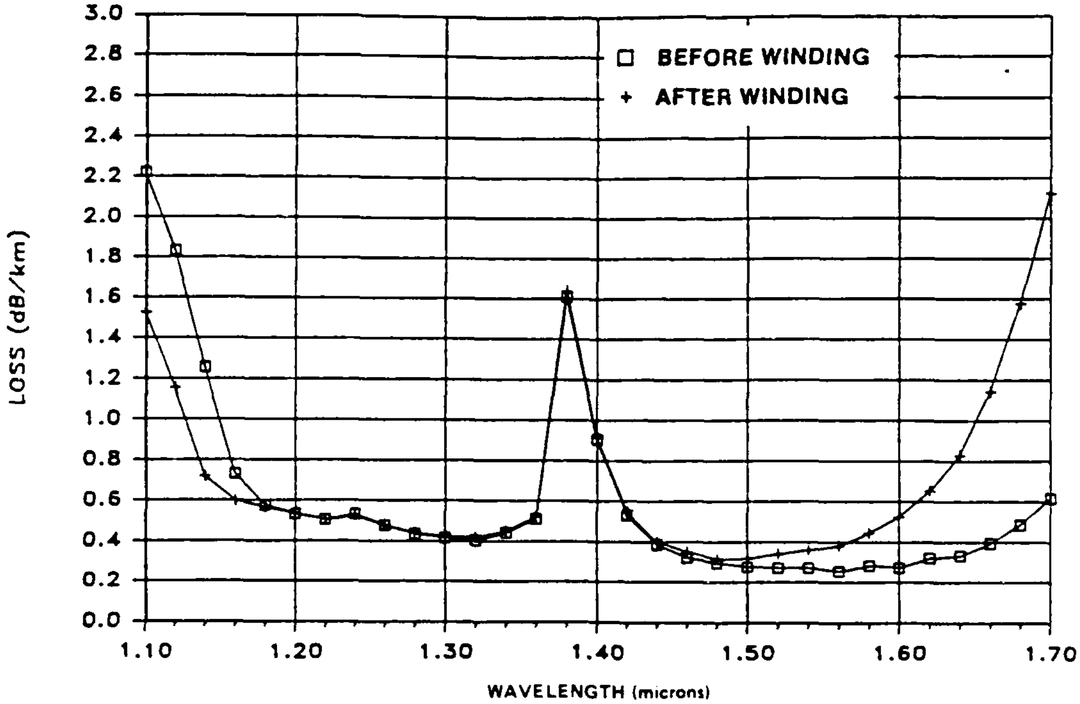

Fig. 6. Spectral Attenuation of Fiber A.

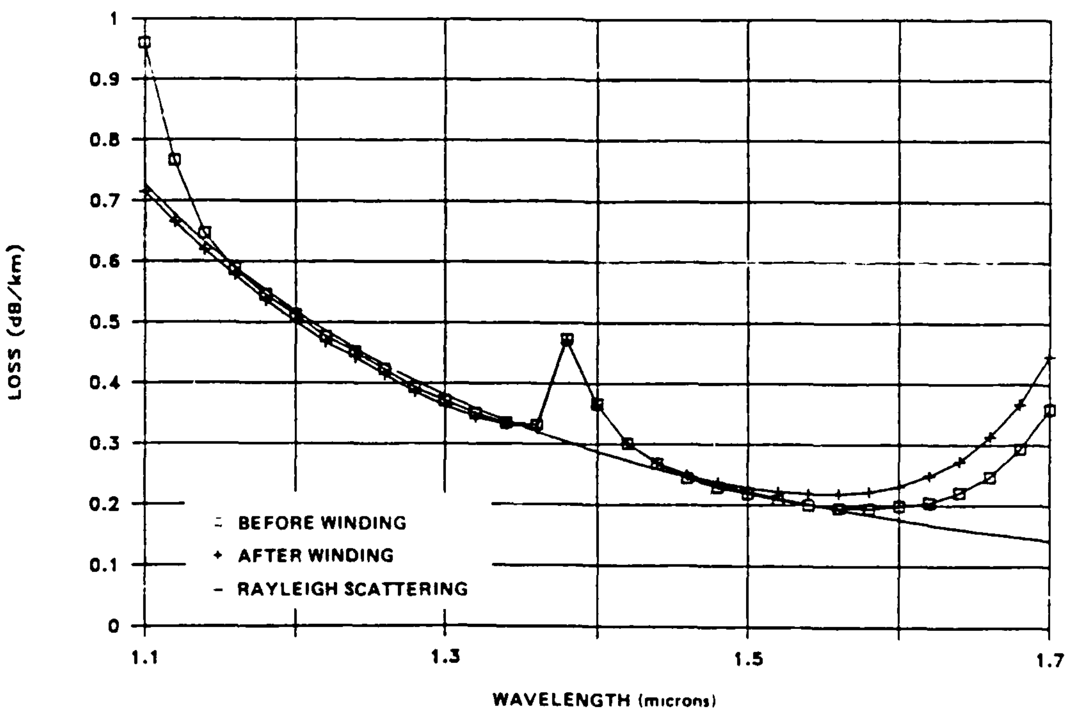

Fig. 7. Spectral Attenuation of Fiber B

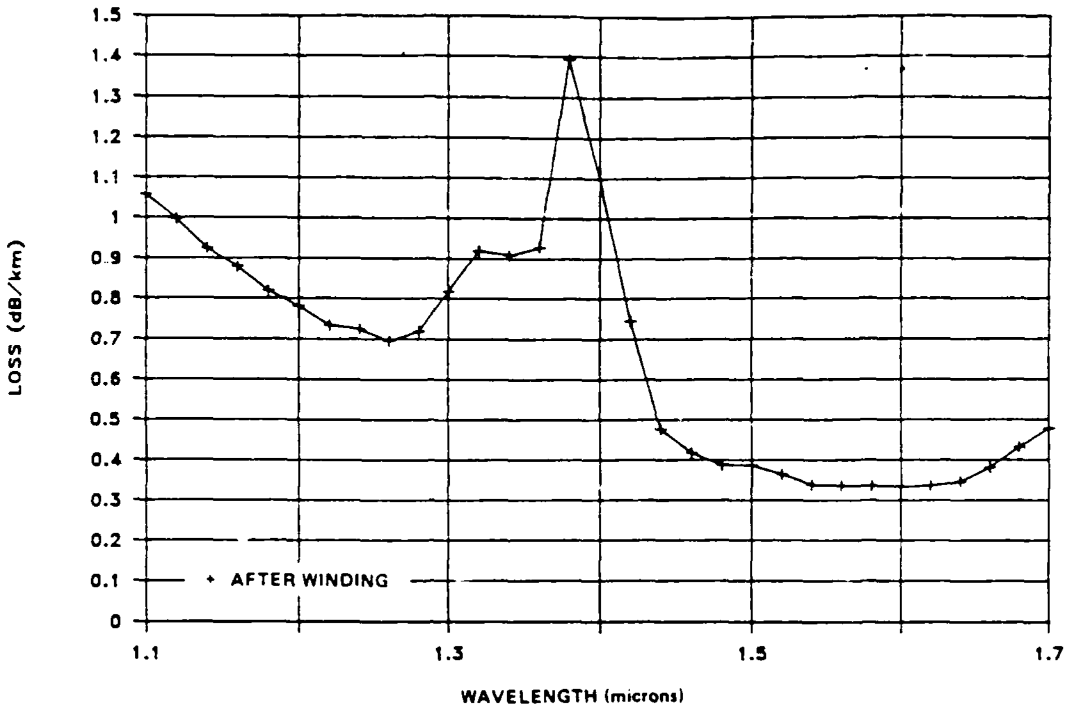

Fig. 8. Spectral Attenuation of Fiber D.

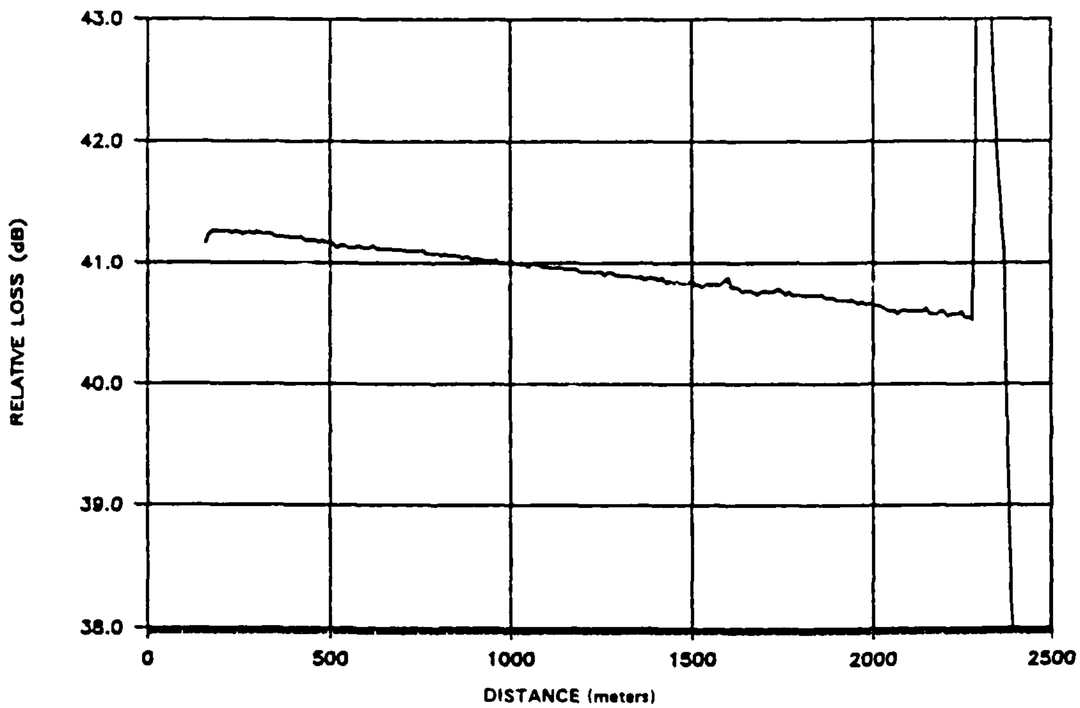

Fig. 9. OTDR @ 1.55 μm of Fiber D.

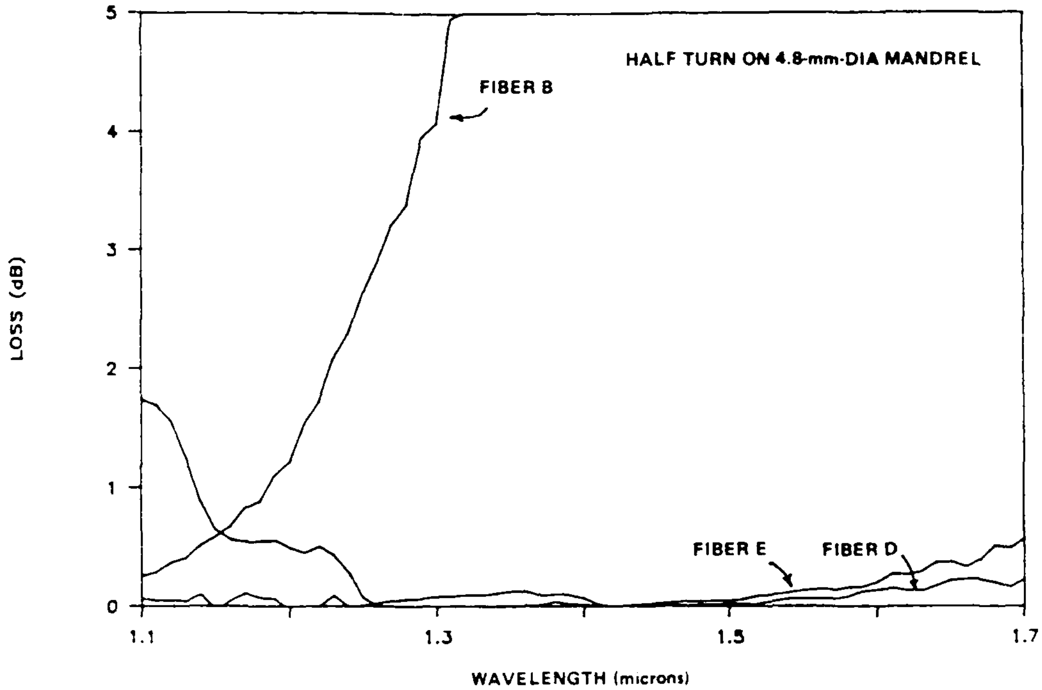

Fig. 10. Bending Losses.